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User Manual

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User Manual

1 Introduction

A basin-wide geomechanical model is developed to predict the minimum horizontal stress in Appalachian Basin of Pennsylvania, Ohio and West Virginia. The Appalachian Basin stress calculator (ABSC) app developed in Matlab R2015a is comprised of three main components: database, algorithm and interface. The database includes a total of 476 wells in the Appalachian Basin with locations, depths of well tops, gamma-ray logs, and density logs. The database also includes other essential properties necessary to calculate stresses, such as pore pressure estimated from production tests (Zagorski et al., 2010), and tectonic strain obtained through calibration (Zhou et al., 2016a). The algorithm adopts a poroelastic stress model to calculate the minimum horizontal stress by describing rocks as transverse isotropy with a vertical symmetry axis (TIV) (Thiercelin and Plumb, 1994). Mechanical properties in the poroelastic model are mainly obtained through interpolation, extrapolation and correlation. Specifically, the evolution of gamma-ray and density over depth are interpolated based on the closest wells. Sonic properties are correlated with gamma-ray based on limited number of wells and the correlation is extrapolated across the basin (Nikoosokhan et al., 2016). The mechanical properties for TIV formations are then correlated with the sonic properties. The interface allows a user to input any location of interest in the Appalachian Basin in Pennsylvania, eastern Ohio and northern West Virginia. It outputs results including the minimum horizontal stresses of the new well, neighboring wells, and wells along a cross section. In the following, the database, algorithm and interface are described, and two examples are given to illustrate how to get the stresses of a new well and those of wells along a cross section.

2 Database

2.1 Well locations and pore pressure

The database includes a total of 476 wells in the Appalachian Basin, with 439 in Pennsylvania, 28 in eastern Ohio, and 9 in northern West Virginia (Figure 1). Gamma-ray and density logs are available for all wells, and those with Marcellus penetrations are limited to 185 among 476 wells. The Marcellus Formation is overpressured over a large portion of the PA Appalachian Plateau (Zagorski et al., 2010), and the pore pressure gradient in Ohio and West Virginia is generally smaller than that in Pennsylvania (Figure 2). For all the wells, the well tops of different mechanical units in the Devonian section are estimated based on multiple sources including gamma-ray logs, density logs and completion reports.

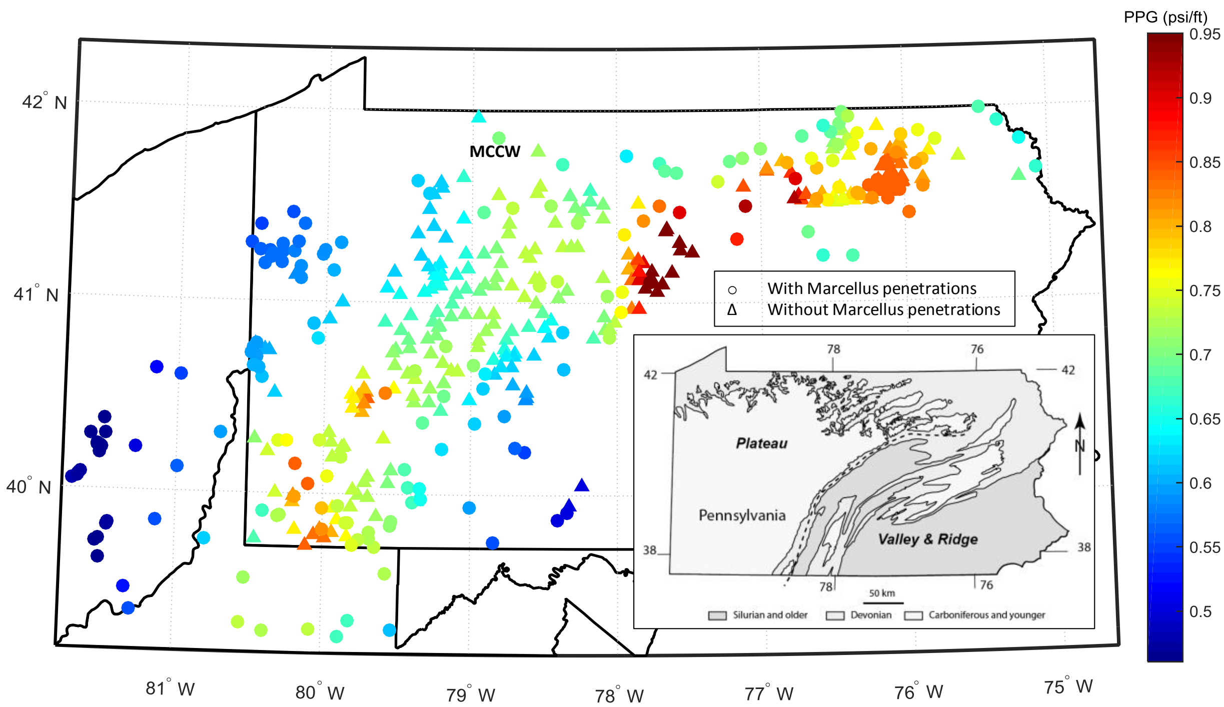

Figure 1: A total of 476 wells with gamma-ray and density logs (circles for 185 wells with Marcellus penetrations and triangles for 291 wells without Marcellus penetrations). The data are colored by pore pressure gradient (PPG) in Marcellus after (Zagorski et al., 2010). Inset geological map divides the geology of Pennsylvania into three units based on age: Silurian and older, Devonian, and Mississippian and younger.

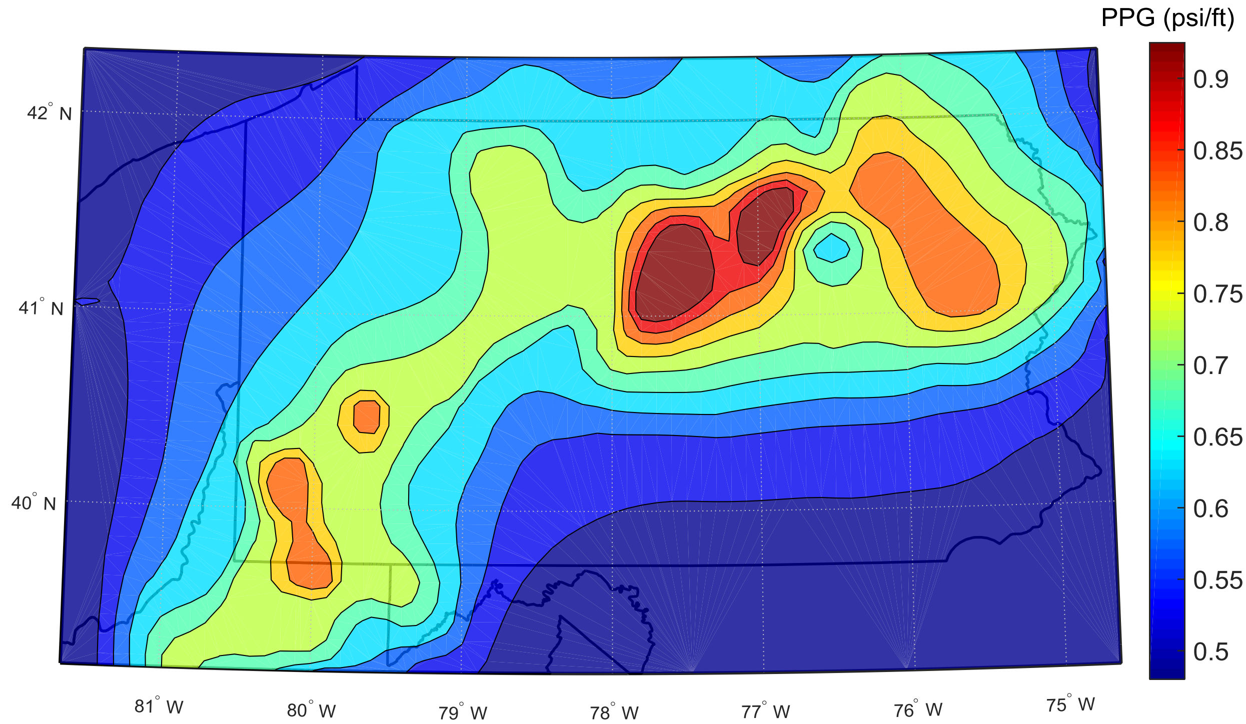

Figure 2: Contour of pore pressure gradient (PPG) in Marcellus in the Appalachian Basin of Pennsylvania and neighboring areas after (Zagorski et al., 2010). The pore pressure gradient in other formations is assumed to be hydrostatic (0.46 psi/ft).

2.2 The McKean County calibration well (MCCW)

A well is drilled in the McKean County in the Appalachian Basin of Pennsylvania (well MCCW in Figure 1) to calibrate the minimum horizontal stress. A full geophysical log suite was collected for the McKean County Calibration Well (MCCW) which penetrates the Marcellus gas shale in its lower density region (Zhou et al., 2016b). *In situ* stresses are measured at ten stations and ultrasonic velocities are measured for 19 sidewall core samples in different formations with seven of them in the Marcellus Formation (Mitra et al., 2016). For the purpose of this study, the Devonian section in the Appalachian Basin is divided into seven mechanical units starting with the Onondaga. Moving upward, these units include the Marcellus, Mahantango, Tully (missing in the MCCW), Geneseo, Brallier, and Upper Devonian (Figure 3). Each of the mechanical units has a unique signature for the combination of gamma-ray log, P-wave velocity log, S-wave velocity log, and density log (Figure 3).

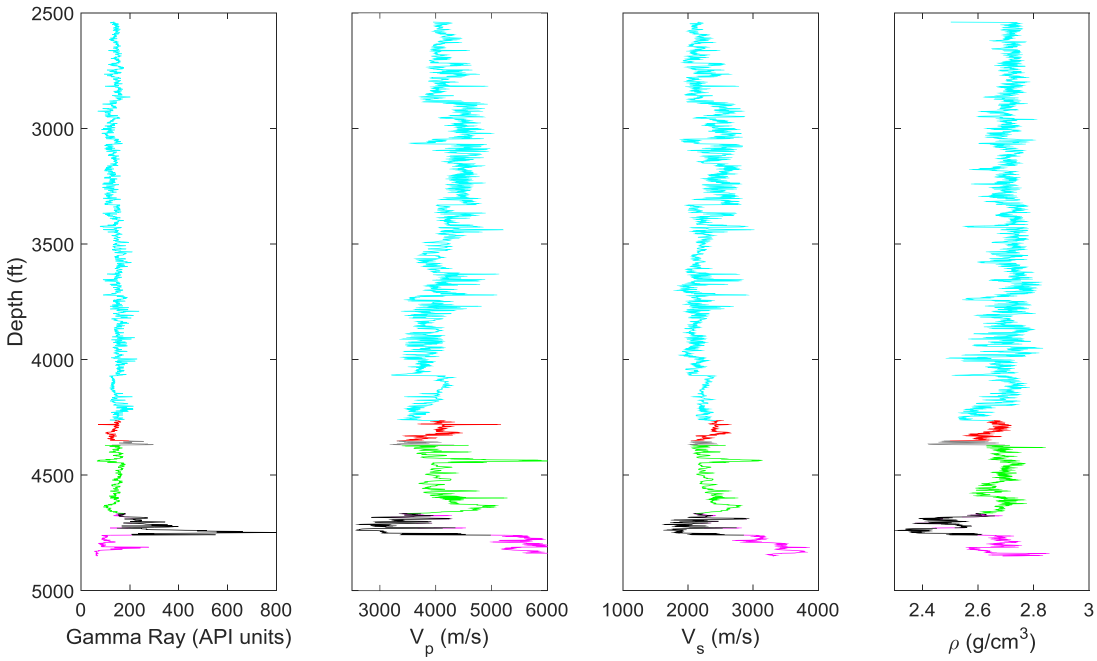

Figure 3: Gamma-ray, P-wave velocity, S-wave velocity, and density logs in the MCCW. The color code identifies the six mechanical units from top to bottom: Upper Devonian (cyan), Brallier (red), Geneseo (gray), Mahantango (green), Marcellus (black), and Onondaga (magenta).

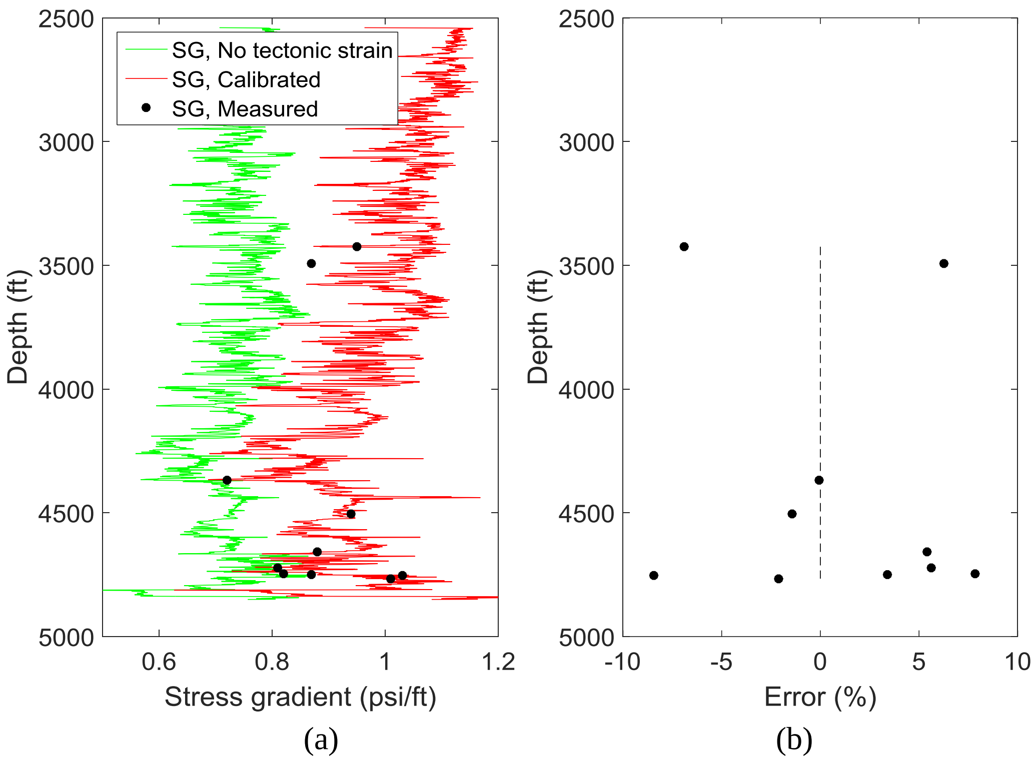

Figure 4: Calibration of minimum horizontal stress gradient (SG) in TIV formations. (a) Green curve is the predicted value using Eq. 1 without a tectonic strain. Red curve is a calculation with a bimodal P_p gradient of 0.71 psi/ft for the Marcellus and a hydrostatic P_p gradient of 0.46 psi/ft for the Onondaga and the section above the Marcellus. (b) Error between calibrated values and measured values for the ten *in situ* stress measurements.

Transverse isotropy is generally used for unfractured laminated rocks such as shales, which are regarded to be isotropic in the bedding plane but anisotropic in the direction normal to the bedding plane (Thiercelin and Plumb, 1994). A poroelastic stress model is used to calculate the minimum horizontal stress by describing rocks as TIV formations (Thiercelin and Plumb, 1994), and the minimum horizontal stress S_{hmin} is expressed as:

$$S_{h\min} = \frac{E_h}{E_v}\frac{\nu_v}{1-\nu_h}\left(S_v - \alpha P_p\right) + \alpha P_p + \left(\frac{E_h}{1-{\nu_h}^2}\right)\varepsilon_{h\min} + \left(\frac{\nu_h E_h}{1-{\nu_h}^2}\right)\varepsilon_{H\max} \tag{1}$$

where S_v is overburden stress, α is Biot's coefficient, P_p is pore pressure, $\varepsilon_{h\min}$ is minimum tectonic strain, and $\varepsilon_{H\max}$ is maximum tectonic strain.

The overburden stress S_v is calculated with rock bulk density of 2.71 g/cm^3, and the Biot's coefficient α is assumed to be 1. The tectonic strains are assumed to be uniform over depth and the maximum tectonic strain is two times the minimum tectonic strain (Song and Hareland, 2012; Thiercelin and Plumb, 1994). A bimodal P_p distribution is used with overpressure ($\Delta P_p/\Delta z$ = 0.71 psi/ft) estimated based on the contour in Figure 2 (Zagorski et al., 2010) in the Marcellus and with hydrostatic pore pressure ($\Delta P_p/\Delta z$ = 0.46 psi/ft) in all other units.

Based on minimum horizontal stresses measured at ten stations and the predicted values, the calibration is conducted by minimizing the function:

$$\sum_{i=1}^{n}\left(S_{h\min} - S_{hi}\right)^2 \tag{2}$$

where n is the number of locations where minimum horizontal stresses are measured, S_{hi} is the i^{th} measured minimum horizontal stress, and S_{hmin} is the corresponding predicted value given in Eq. 1 for TIV formations.

Stress calibrations are given in terms of stress gradients. The predicted minimum horizontal stress gradient is underestimated using just poroelastic deformation (i.e., Eq. 1) without the superposition of a component of tectonic strain (Figure 4a). To calibrate stress, the maximum tectonic strain ε_{Hmax} is continually adjusted until the function in Eq. 2 is minimized. The calibrated values match the *in situ* data (i.e., the ten Schlumberger MDT stress tests) and the error between predicted stress and the MDT measurement is generally within 10% when the maximum horizontal strain is a constant 0.15 *m*strain (1 *m*strain = 0.001) in the entire Devonian section (Figure 4b). The average error, defined as the average of absolute errors of these ten depths, is 5.7%.

3 Algorithm

There are several procedures in the algorithm implemented in the app to calculate the minimum horizontal stress, as listed below:

1. Calculate the evolution of gamma-ray and density over depth of a new well by interpolation.
2. Correlate sonic properties and gamma-ray.
3. Correlate mechanical properties and sonic properties.
4. Calculate minimum horizontal stress based on the poroelastic model.

3.1 Step 1: Interpolate gamma-ray and density of a new well

For a new well, the essential parameters (e.g., depths of well tops, gamma-ray and density) are interpolated based on five closest wells. As the logs with Marcellus penetrations are limited to 185 wells while the well tops of different mechanical units are available for all the 476 wells, different neighboring wells are used to calculate different parameters. Specifically, the depths of well tops are interpolated based on five closest wells among all of the 476 wells, while gamma-ray and density are interpolated based on five closest wells among 185 wells with Marcellus penetrations. The parameters of the new well are calculated based on inverse distance weighting as follows:

$$y = \sum_{i=1}^{N} w_i y_i \text{ with } w_i = \frac{1/l_i^2}{\sum_{i=1}^{N} 1/l_i^2} \tag{3}$$

where y is a parameter of the new well (e.g., depth of well top, gamma-ray and density), y_i is the corresponding parameter of the i^{th} closest well, w_i is the inverse distance weight of the i^{th} closest well, l_i is the distance from the i^{th} closest well to the new well, and N is the number of closest wells with $N = 5$.

3.2 Step 2: Correlate sonic properties and gamma-ray

Sonic well logs are important to derive mechanical properties necessary for stress evaluation, but they are only available in very limited number of wells. Thus correlations are established based on selected wells and then extrapolated across the basin. Among the 37 selected wells used to correlate P-wave velocity and gamma-ray, 22 wells with S-wave travel time are used to correlate S-wave velocity and P-wave velocity (Figure 5).

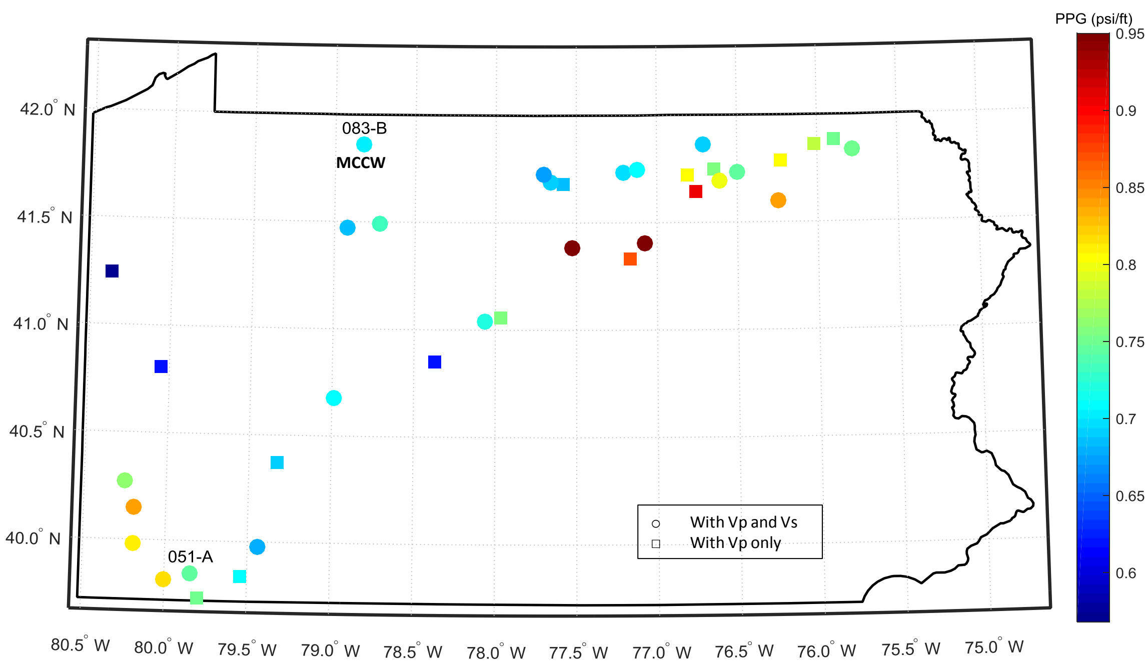

Figure 5: Locations of 37 wells with Marcellus penetrations and both gamma-ray plus sonic log data that include at least P-wave travel time. These 37 wells are used to correlate P-wave velocity and gamma-ray, and 22 wells with both velocities marked with circles are used to correlate S-wave velocity and P-wave velocity, and the two wells (083-B and 051-A) are used to correlate elastic stiffnesses C_{66} and C_{44}.

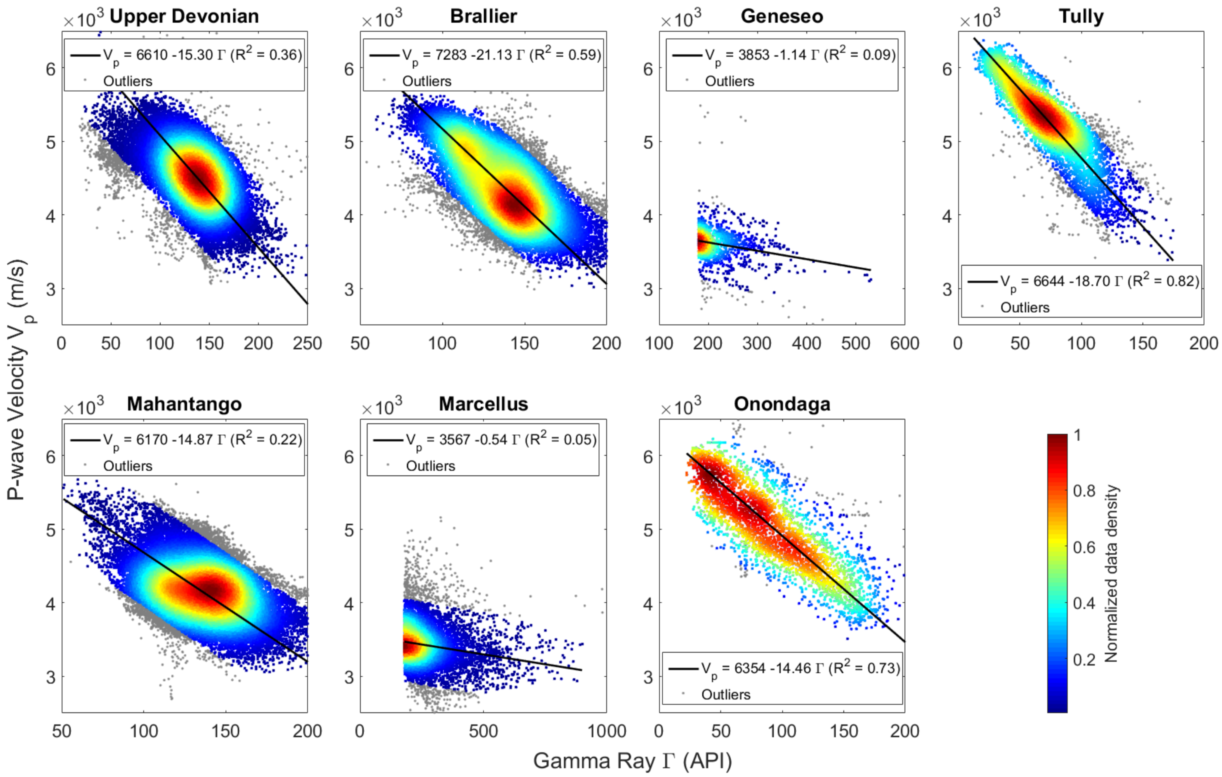

Figure 6: Correlation between vertical P-wave velocity and gamma-ray based on 37 wells in seven mechanical units in the Appalachian Basin from top to bottom: Upper Devonian, Brallier, Geneseo, Tully, Mahantango, Marcellus, and Onondaga.

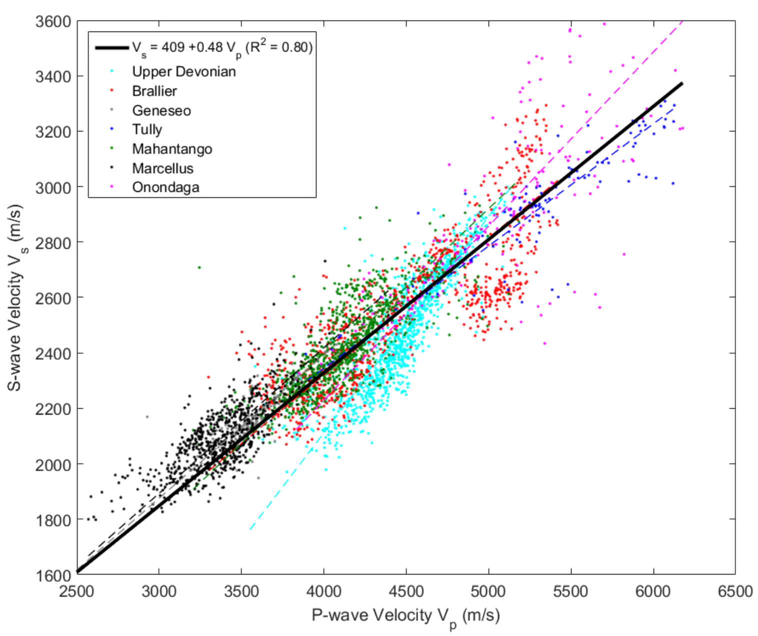

Figure 7: Correlation between vertical S-wave velocity and P-wave velocity based on 22 wells (data averaged over 5~20 ft intervals).

Linear correlations between vertical P-wave velocity and gamma-ray are established in seven mechanical units in the Appalachian Basin from top to bottom: Upper Devonian, Brallier, Geneseo, Tully, Mahantango, Marcellus, and Onondaga, by dropping outliers with large residuals (Figure 6) (Nikoosokhan et al., 2016):

$$V_p = b + k\Gamma \tag{4}$$

where V_p is vertical P-wave velocity with the unit of m/s, Γ represents gamma-ray with API unit, *b* and *k* are intercept and slope, respectively, and the equations in different formations are summarized in Table 1.

Table 1: Correlation between vertical P-wave velocity and gamma-ray in different formations

Mechanical unit	Equation	R^2
Upper Devonian	$V_p = 6610 - 15.30\Gamma$	0.36
Brallier	$V_p = 7283 - 21.13\Gamma$	0.59
Geneseo	$V_p = 3853 - 1.14\Gamma$	0.09
Tully	$V_p = 6644 - 18.70\Gamma$	0.82
Mahantango	$V_p = 6170 - 14.87\Gamma$	0.22
Marcellus	$V_p = 3567 - 0.54\Gamma$	0.05
Onondaga	$V_p = 6354 - 14.46\Gamma$	0.73

The P-wave velocity and gamma-ray generally correlate well except in the two black shales (i.e., Geneseo and Marcellus). The sonic velocities in Marcellus are influenced by multiple factors such as pore pressure and carbonate content, in addition to total organic carbon (TOC) which is approximated by gamma-ray (Zhou et al., 2016b). The gamma-ray is cut off at 180 API for the two black shales in the correlation. For the interbedded limestone in Marcellus with gamma-ray lower than 180 API, P-wave velocity is estimated to be the average value predicted by the two equations in Marcellus and Onondaga in Table 1. Similarly, P-wave velocity in Geneseo with gamma-ray lower than 180 API is estimated to be the average value predicted by the two equations in Geneseo and Tully.

The correlations between vertical S-wave velocity and P-wave velocity are also regressed in different formations. The correlations in different formation as represented by the dash lines are generally close to the correlation based on all formations as represented by the solid line (Figure 7). Thus, a simple correlation between S-wave velocity and P-wave velocity based on all formations is used, and the goodness of fit is suggested by high value of R^2 (0.80):

$$V_s = 409 + 0.48V_p \tag{5}$$

where V_s is vertical S-wave velocity with the unit of m/s.

3.3 Step 3: Correlate mechanical properties and sonic properties

There are five independent elastic stiffnesses in the TIV model, namely C_{33}, C_{44}, C_{66}, C_{13}, and C_{11} (Higgins et al., 2008). The first two stiffnesses can be conveniently determined based on vertical P- and S-wave velocities and rock bulk density ρ in a vertical well, with $C_{33} = \rho V_p^2$ and $C_{44} = \rho V_s^2$ (Horne and Walsh, 2014). The third stiffness C_{66} can be determined based on either Stoneley wave in a vertical well or horizontal shear wave in a horizontal well (Horne and Walsh, 2014; Sinha et al., 1994). Here, a simple correlation is established between C_{66} and C_{44} based on available data in two vertical wells (083-B and 051-A in Figure 5), as shown in Figure 8 and expressed as follows:

$$C_{66} = 0.56C_{44} + 13.34 \tag{6}$$

where the unit of C_{44} and C_{66} is GPa.

The last two stiffnesses can be expressed as functions of the first three stiffnesses, $C_{13} = C_{33} - 2C_{44}$, and $C_{11} = C_{33} - 2C_{44} + 2C_{66}$ (Higgins et al., 2008), by introducing ANNIE assumptions: $\delta = 0$ and $C_{12} = C_{13}$ (Schoenberg et al., 1996), where δ is a dimensionless anisotropy parameter (Thomsen, 1986).

After obtaining the stiffnesses in the TIV model, the vertical and horizontal Young's moduli and Poisson's ratios can be expressed as follows (Higgins et al., 2008):

$$
\begin{aligned}
E_v &= C_{33} - 2\frac{C_{13}^2}{C_{11}+C_{12}} \\
E_h &= \frac{(C_{11}-C_{12})(C_{11}C_{33}-2C_{13}^2+C_{12}C_{33})}{C_{11}C_{13}-C_{13}^2} \\
v_v &= \frac{C_{13}}{C_{11}+C_{12}} \\
v_h &= \frac{C_{33}C_{12}-C_{13}^2}{C_{33}C_{11}-C_{13}^2}
\end{aligned}
\tag{7}
$$

where E_v and E_h are vertical and horizontal Young's modulus, respectively, and v_v and v_h are vertical and horizontal Poisson's ratio, respectively.

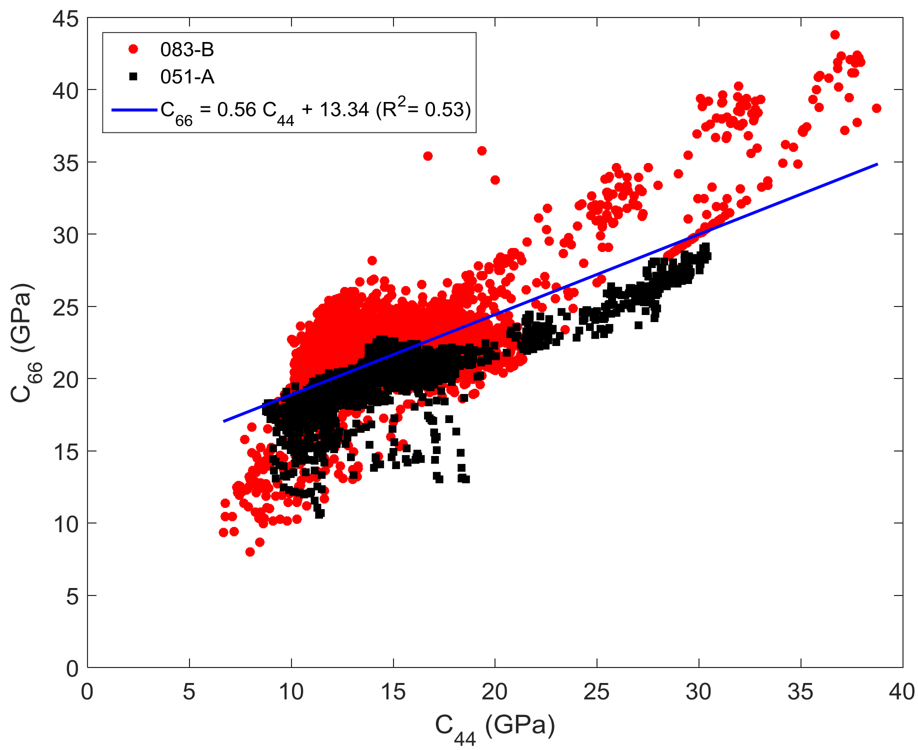

Figure 8: Correlation between elastic stiffness C_{66} and C_{44} based on two wells.

3.4 Step 4: Calculate minimum horizontal stress

The minimum horizontal stress S_{hmin} can be readily predicted based on the poroelastic model in Eq. 1, with the tectonic strains ($\varepsilon_{h\min}$ and $\varepsilon_{H\max}$), elastic properties (E_v, E_h, v_v and v_h), pore pressure P_p, overburden stress S_v, and Biot's coefficient α. The basin-wide variation of elastic properties and pore pressure are considered with some other parameters kept the same as those in the MCCW. Specifically, the tectonic strains calibrated through the MCCW are extrapolated across the basin. The bimodal P_p distribution is used and the pore pressure gradient in Marcellus is estimated based on the contour in Figure 2 (Zagorski et al., 2010). The overburden stress S_v is calculated with rock bulk density of 2.71 g/cm^3, and the Biot's coefficient α is assumed to be 1.

4 Interface

4.1 Installation

The installation of the app ABSC requires the installation of Matlab R2015a or an updated version, and it is straightforward by double clicking the installation file "ABSC.mlappinstall" followed by clicking "Install" (Figure 9). The "ABSC" icon is then shown under the APPS tab in Matlab (Figure 10). The user interface appears by clicking the "ABSC" icon, with four blanks corresponding to the latitudes and longitudes of two new wells (Figure 11). The user can either input the coordinates of one or two wells, and two examples are given as follows.

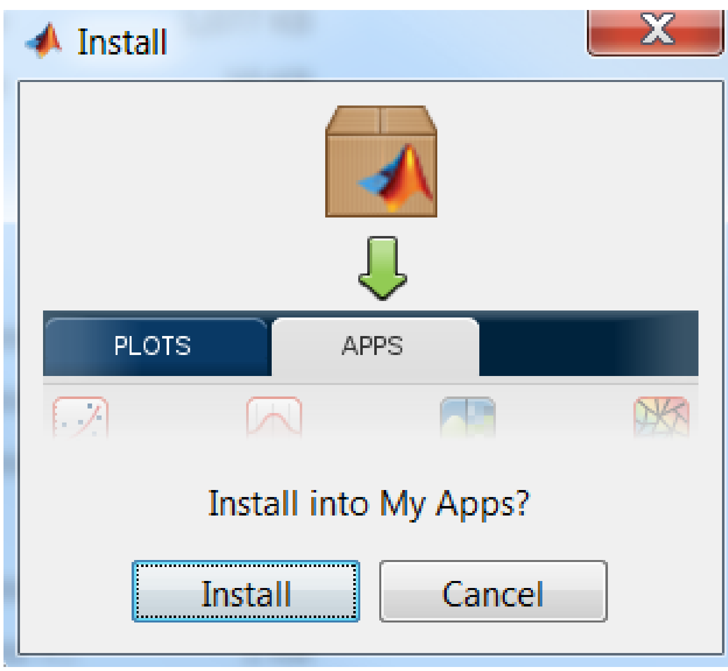

Figure 9: Installation of the ABSC app.

Figure 10: Icon of the ABSC app after installation.

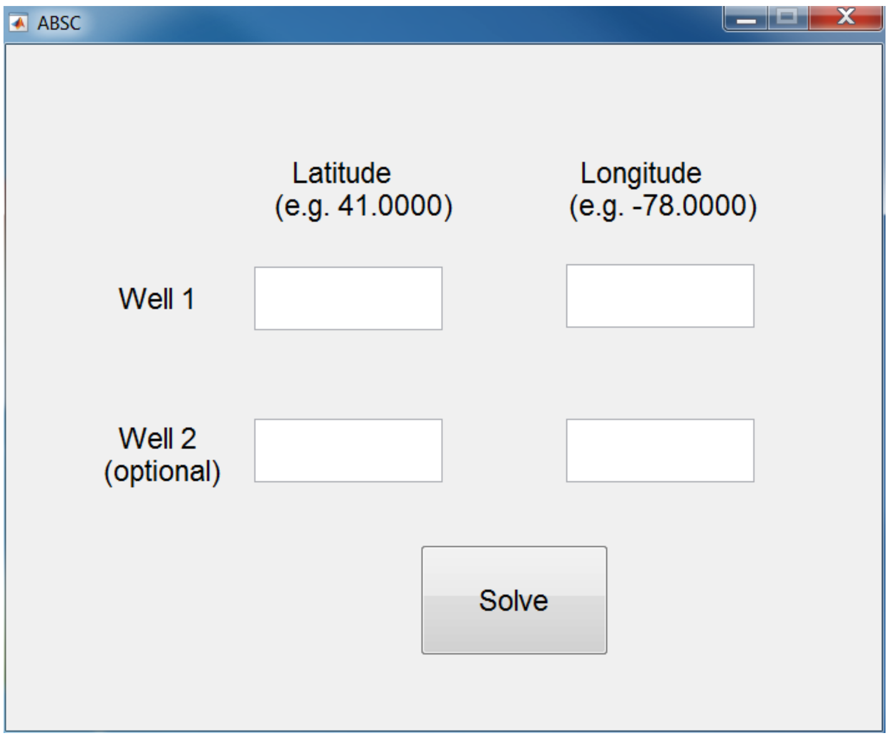

Figure 11: User interface of the ABSC app.

4.2 One new well

An example is given first to calculate results including the minimum horizontal stress of a new well in McKean County. The latitude and longitude are 41.8º and -78.8º, respectively, which are input in the user interface in Figure 12. By clicking the "Solve" button, the results are then shown in several figures. The map in Figure 13 shows the locations of the new well, five closest wells (A, B, C, D, and E), and five closest wells (1, 2, 3, 4 and 5) with Marcellus penetrations. Among the five closest wells (A, B, C, D, and E), only one well (i.e., well A) has Marcellus penetration. The gamma-ray, density and pore pressure gradient of the new well and five closest wells (1, 2, 3, 4 and 5) with Marcellus penetrations are shown in Figure 14, Figure 15, and Figure 16, respectively. For the new well, the gamma-ray, density, velocities, moduli, Poisson's ratios, pore pressure gradient, and minimum horizontal stress gradient are summarized in Figure 17. The minimum horizontal stress gradient generally increases with shallower depth for the new well and five closest wells (Figure 18). The minimum horizontal stress in Marcellus with overpressure is generally larger than that in the adjacent Mahantango with hydrostatic pore pressure, and it is generally smaller than that in the adjacent Onondaga with larger elastic stiffness and tectonic stress (Figure 19). The superposition of gamma-ray and minimum horizontal stress gradient allows one to conveniently evaluate the stress gradient in different formations (Figure 20).

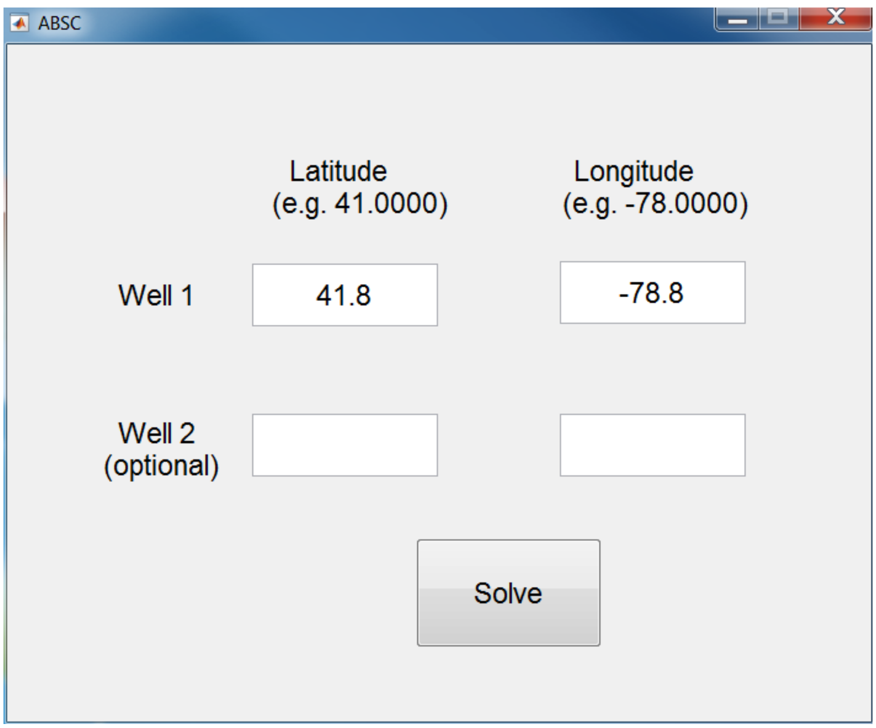

Figure 12: User interface with location of one well.

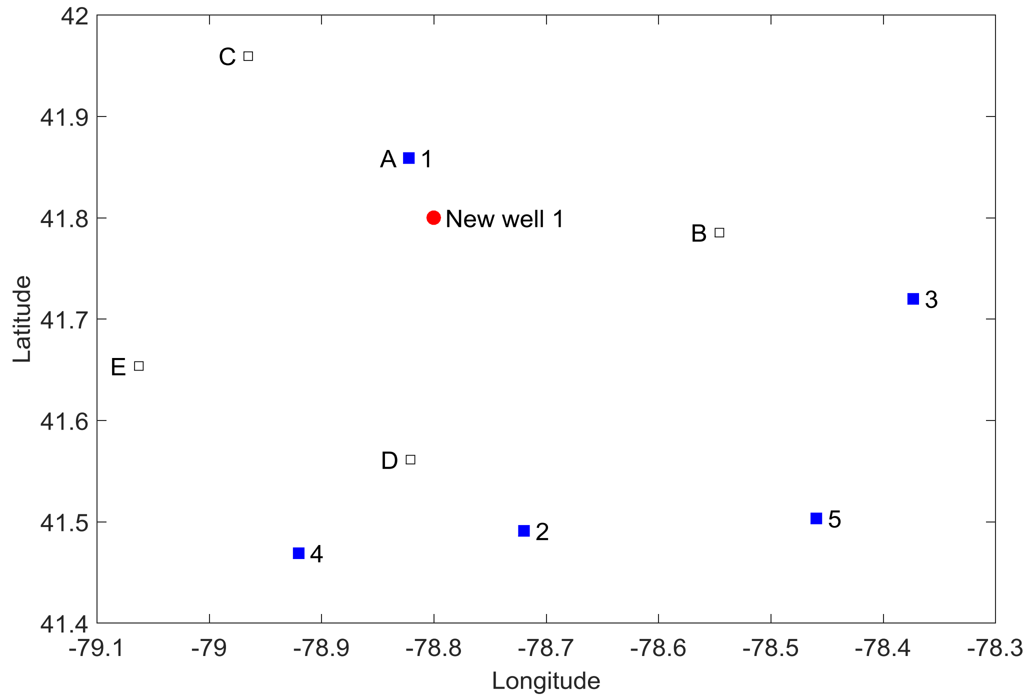

Figure 13: Map of a new well, five closest wells (A,B,C,D,E) and five closet wells (1,2,3,4,5) with Marcellus penetrations. Among the five closest wells (A, B, C, D, and E), only one well (i.e., well A) has Marcellus penetration.

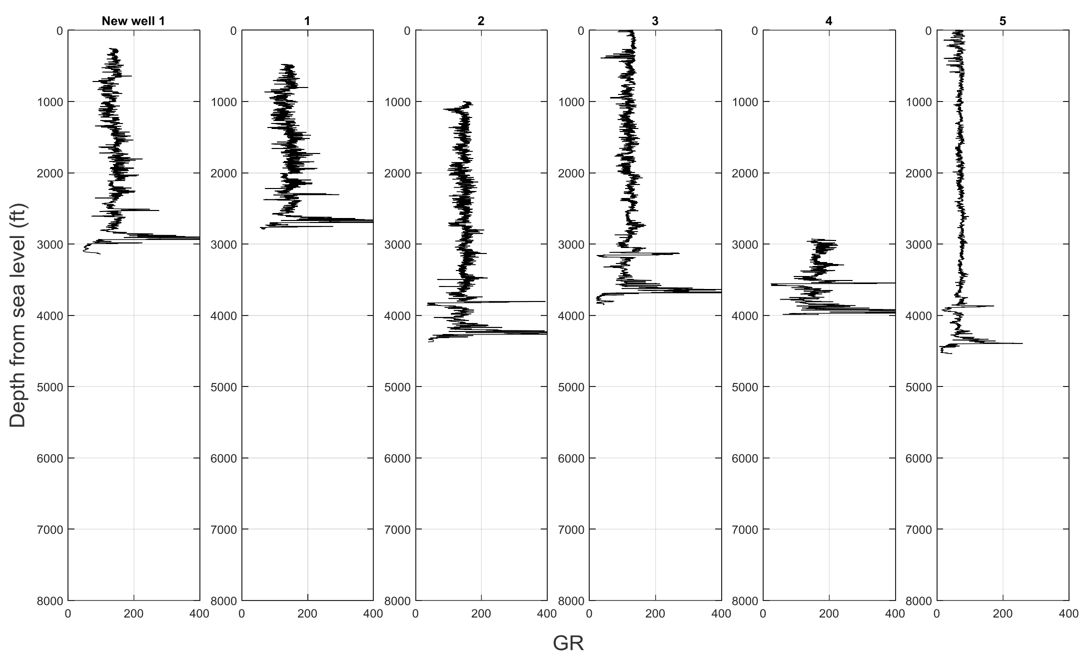

Figure 14: Gamma-ray of a new well and five closest wells with Marcellus penetrations.

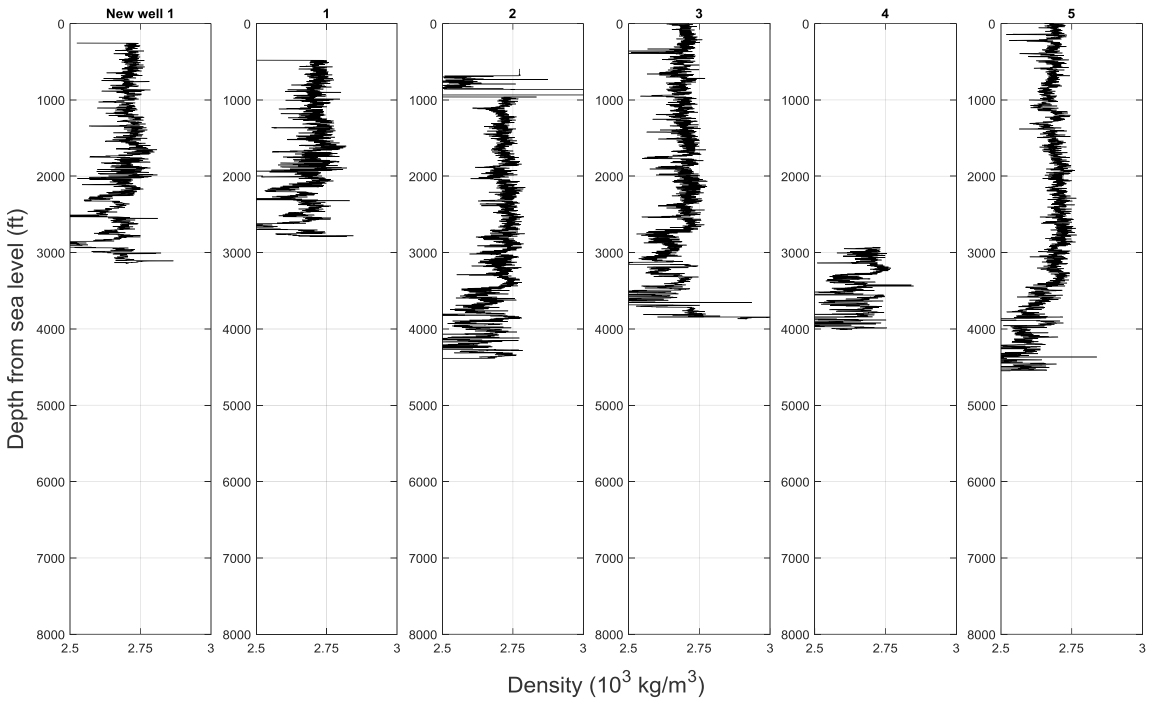

Figure 15: Density of a new well and five closest wells with Marcellus penetrations.

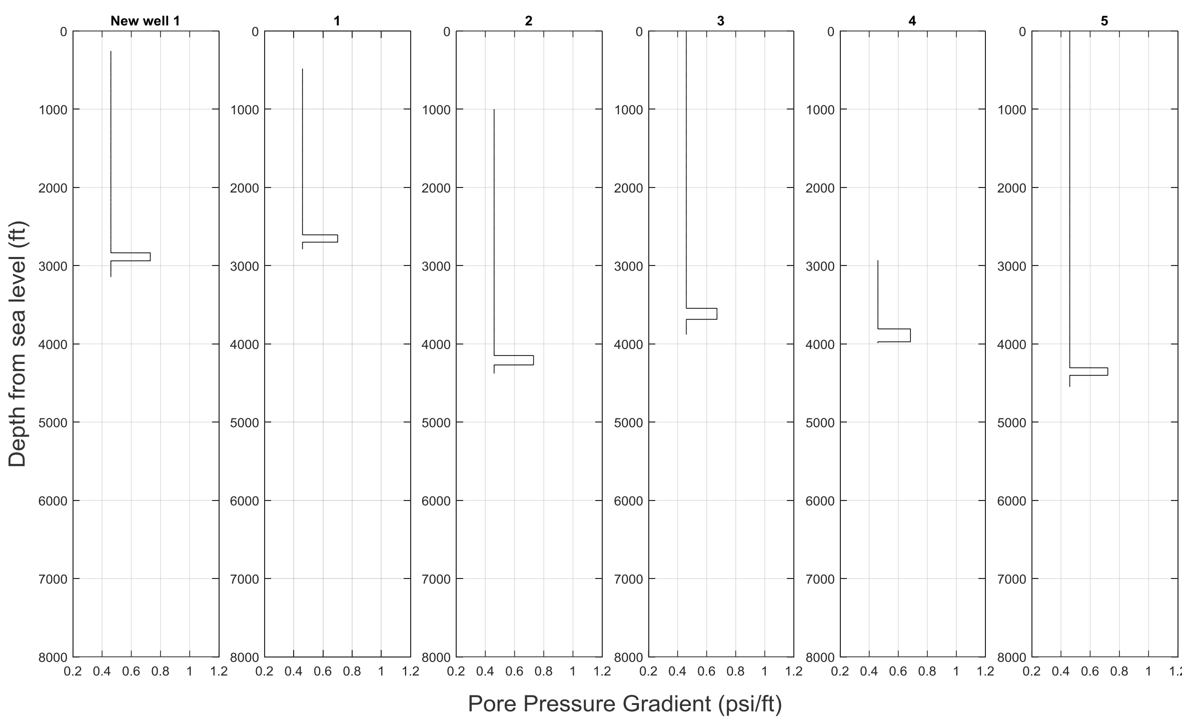

Figure 16: Pore pressure gradient of a new well and five closest wells with Marcellus penetrations.

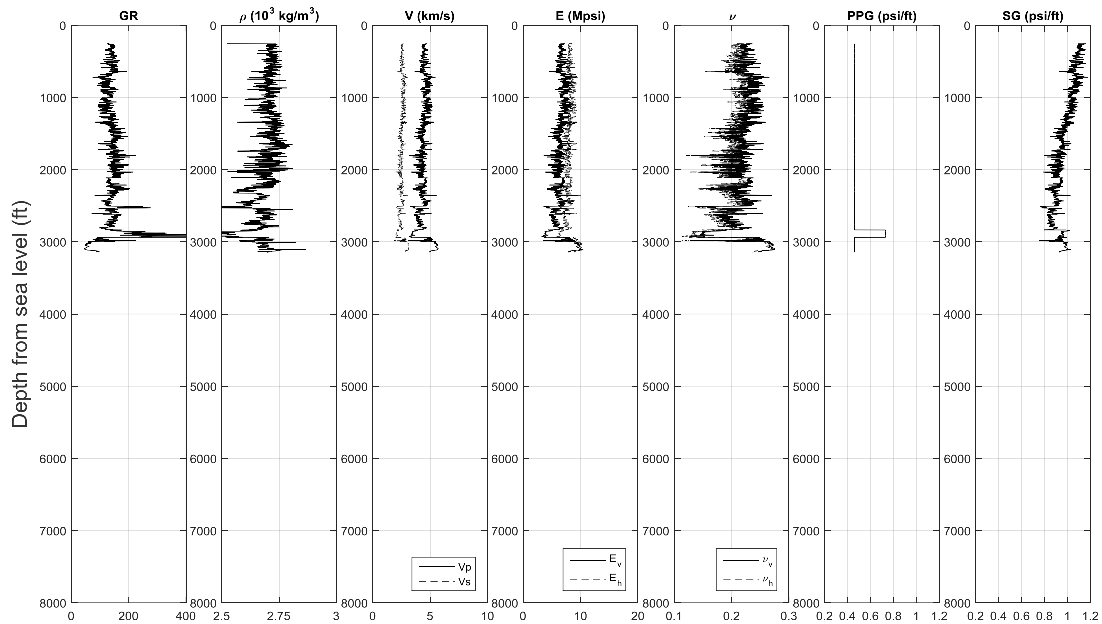

Figure 17: Gamma-ray, density, velocities, moduli, Poisson's ratios, pore pressure gradient and minimum horizontal stress gradient of a new well.

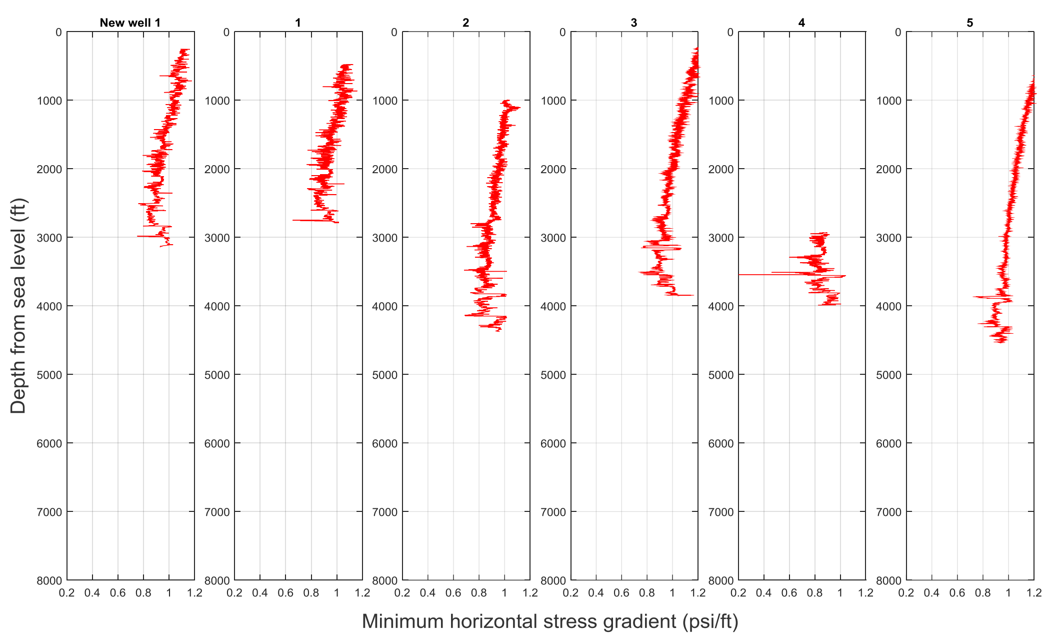

Figure 18: Minimum horizontal stress gradient of a new well and five closest wells with Marcellus penetrations.

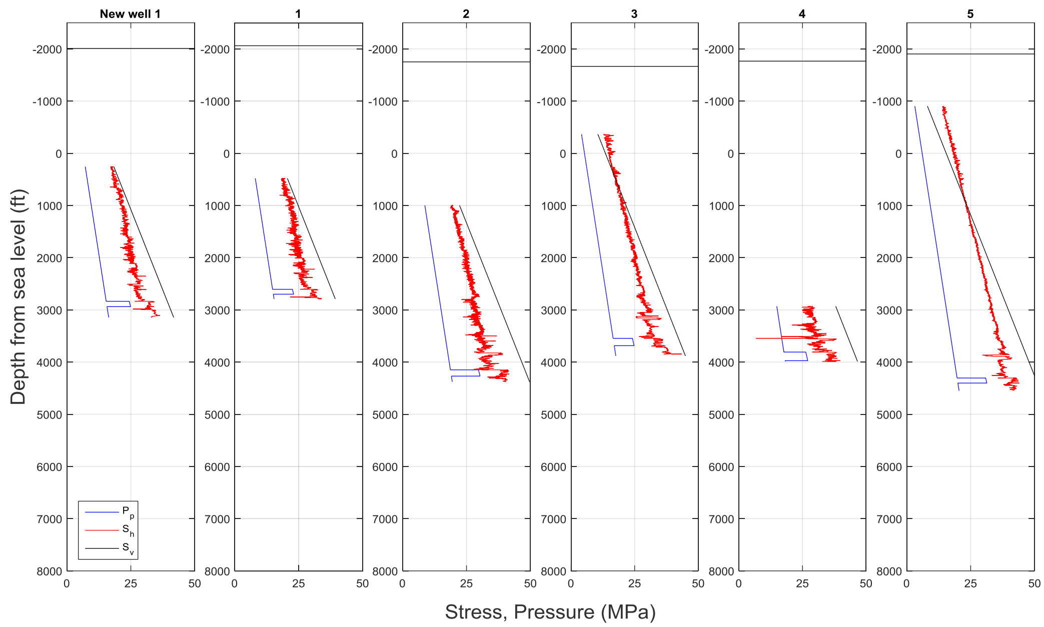

Figure 19: Pore pressure, Minimum horizontal stress, and overburden stress of a new well and five closest wells with Marcellus penetrations. The ground level in each well is represented by a horizontal line.

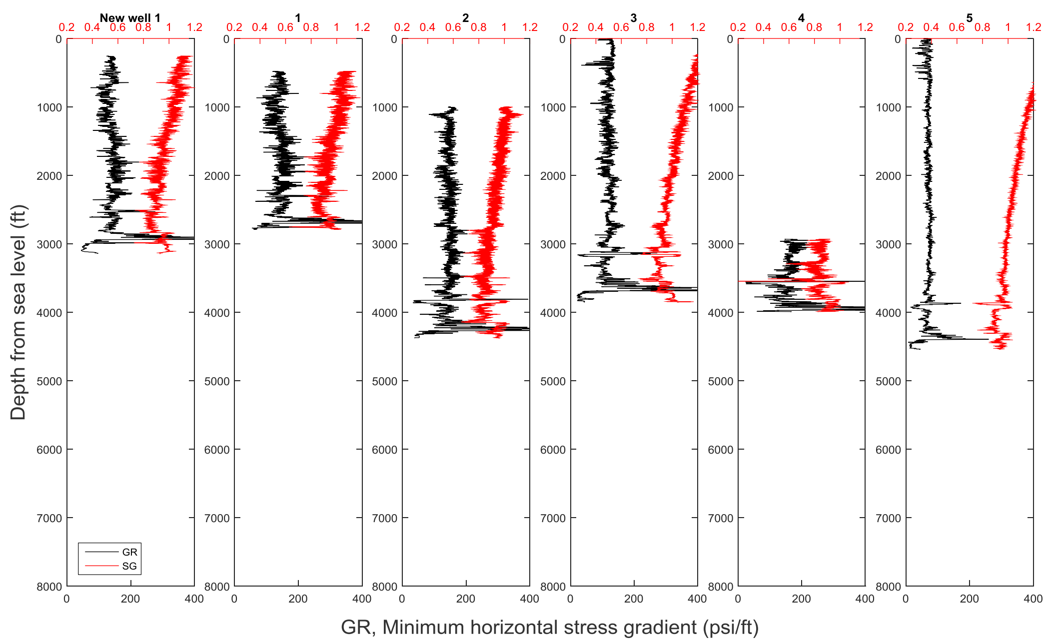

Figure 20: Superposition of gamma-ray and minimum horizontal stress gradient of a new well and five closest wells with Marcellus penetrations.

4.3 Two new wells

An example is given here to calculate the minimum horizontal stresses of wells along a cross section. One well is located in Tioga County with latitude of 41.8 ^{o} and longitude of -77.2 ^{o}, and the other well is located in Susquehanna County with latitude of 41.8 ^{o} and longitude of -75.9 ^{o}. The coordinates are input in the user interface in Figure 21. The map in Figure 22 shows the two new wells and six wells (1, 2, 3, 4, 5 and 6) along the cross section with Marcellus penetrations. Similar as the results by inputting one new well, the results by inputting two new wells include the gamma-ray, density and pore pressure gradient for wells along the cross section (Figure 23, Figure 24 and Figure 25), the minimum horizontal stress gradient (Figure 26), the pore pressure, minimum horizontal stress and vertical stress (Figure 27), and the superposition of gamma-ray and minimum horizontal stress gradient (Figure 28).

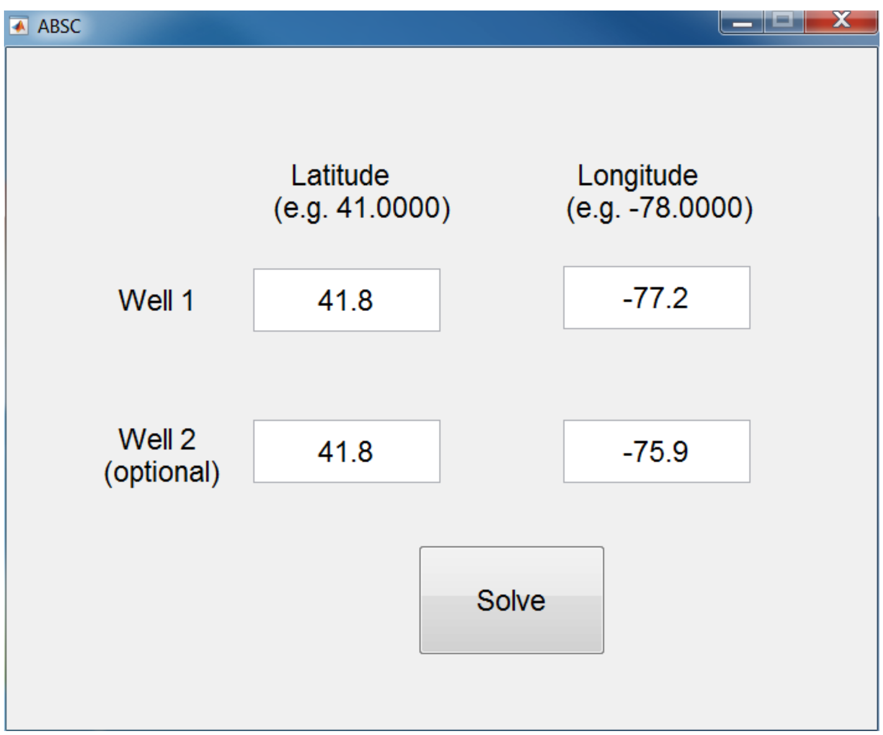

Figure 21: User interface with locations of two wells.

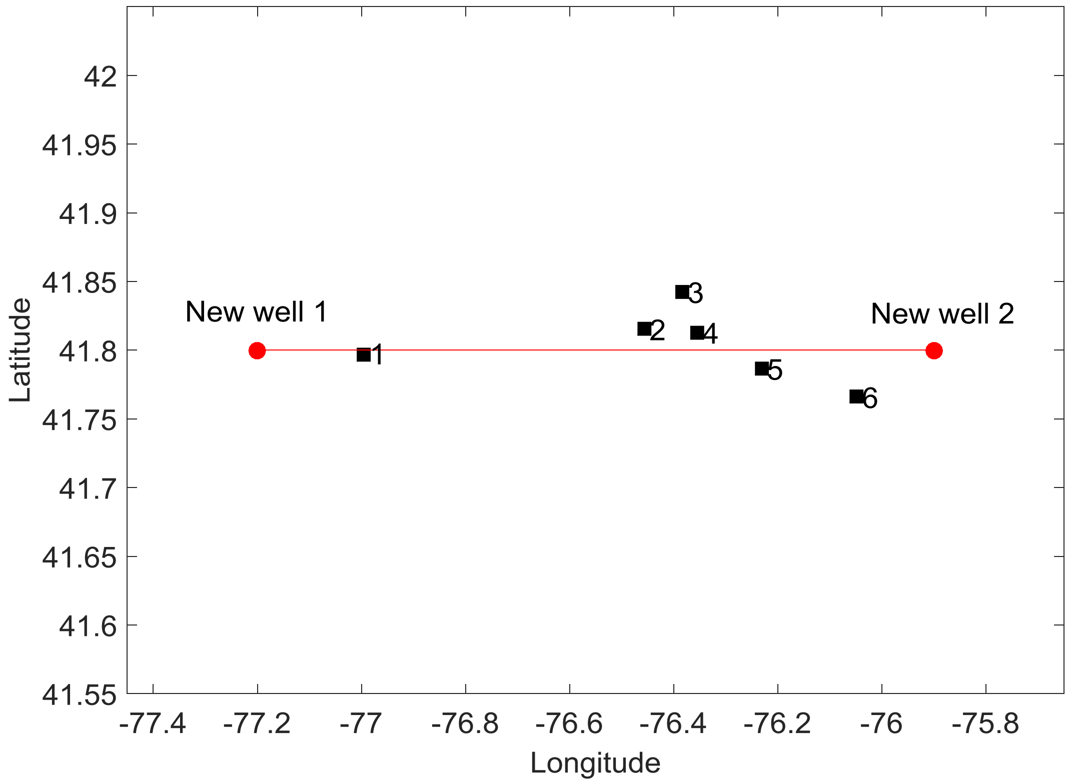

Figure 22: Map of two new wells and six wells with Marcellus penetrations along the cross section.

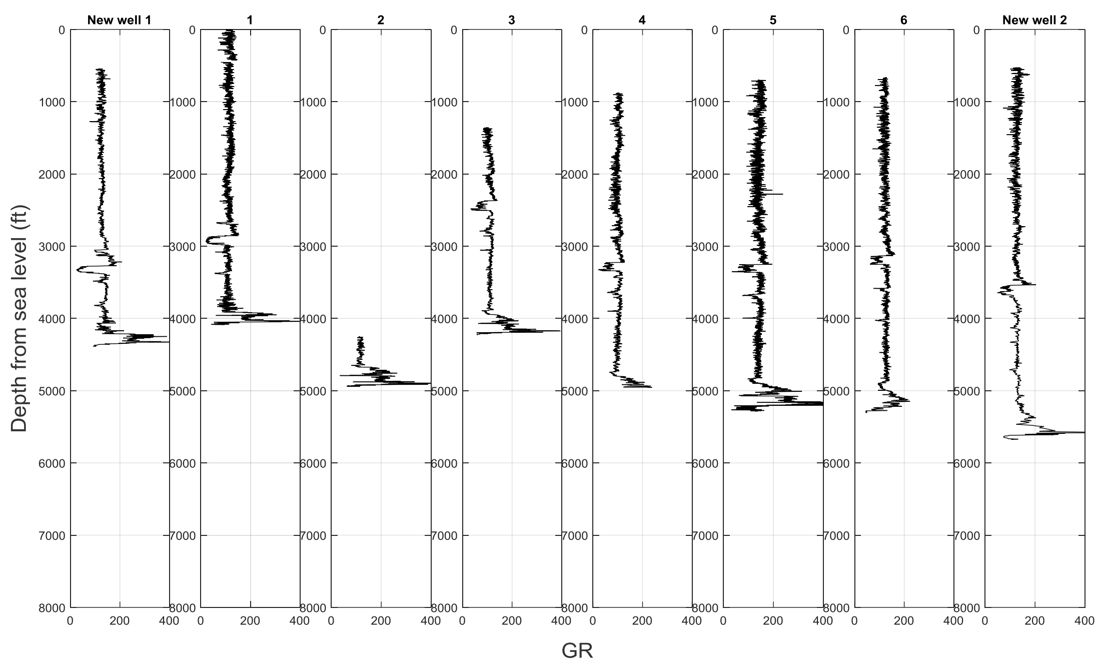

Figure 23: Gamma-ray of two new wells and six wells along the cross section with Marcellus penetrations.

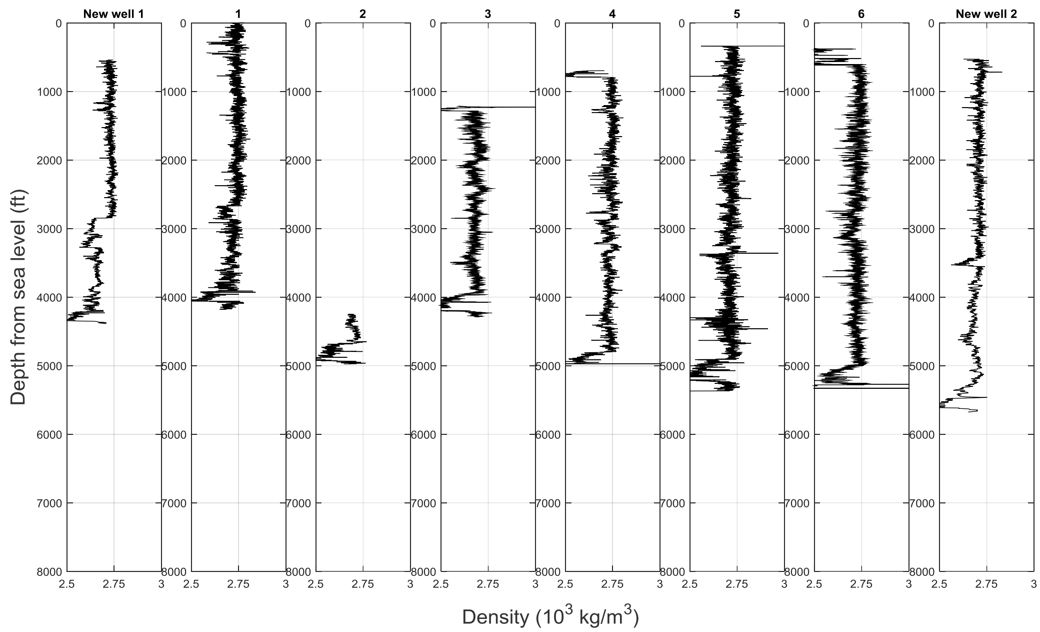

Figure 24: Density of two new wells and six wells along the cross section with Marcellus penetrations.

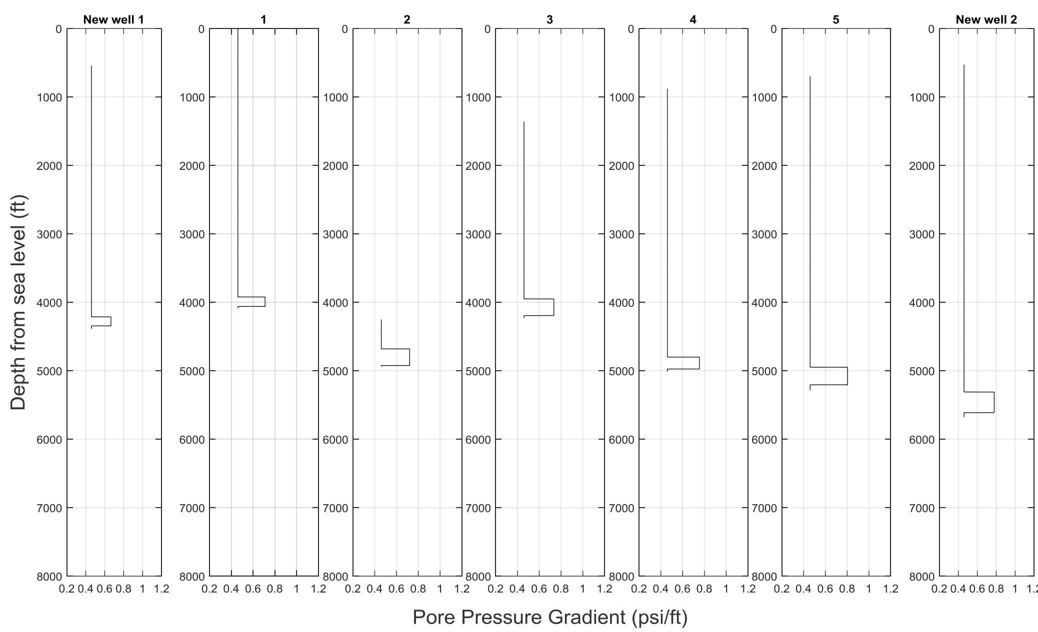

Figure 25: Pore pressure gradient of two new wells and six wells along the cross section with Marcellus penetrations.

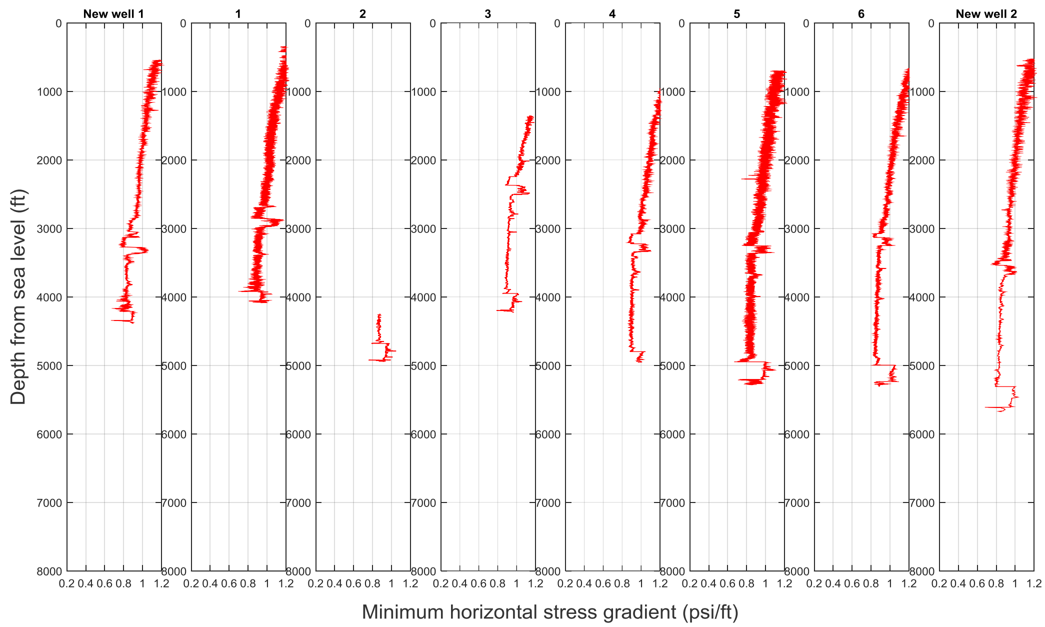

Figure 26: Minimum horizontal stress gradient of two new wells and six wells along the cross section with Marcellus penetrations.

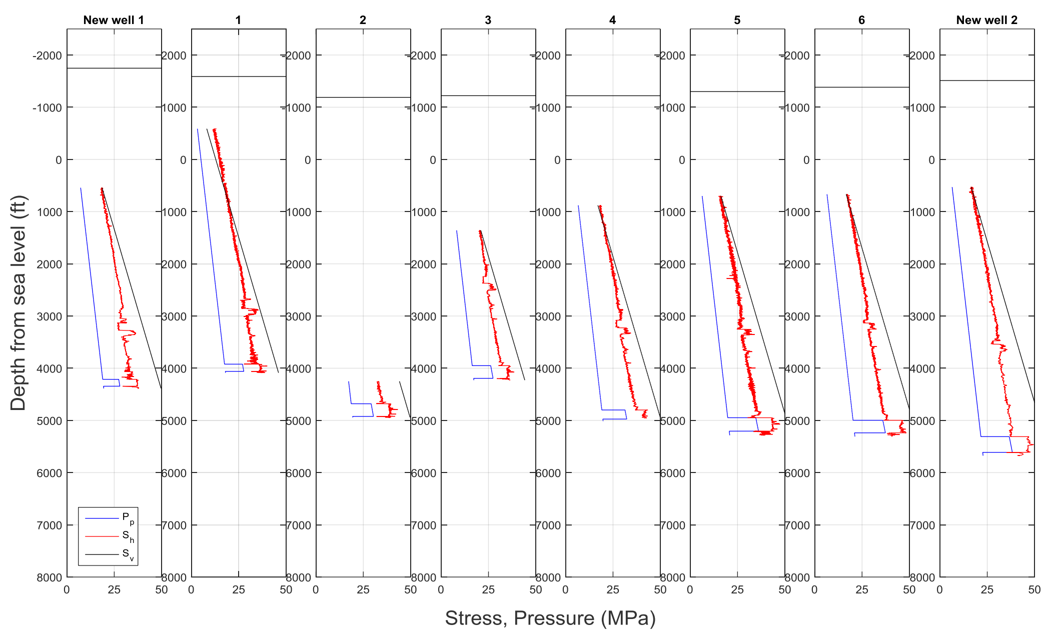

Figure 27: Pore pressure, Minimum horizontal stress, and overburden stress of a new well and five closest wells with Marcellus penetrations. The ground level in each well is represented by a horizontal line.

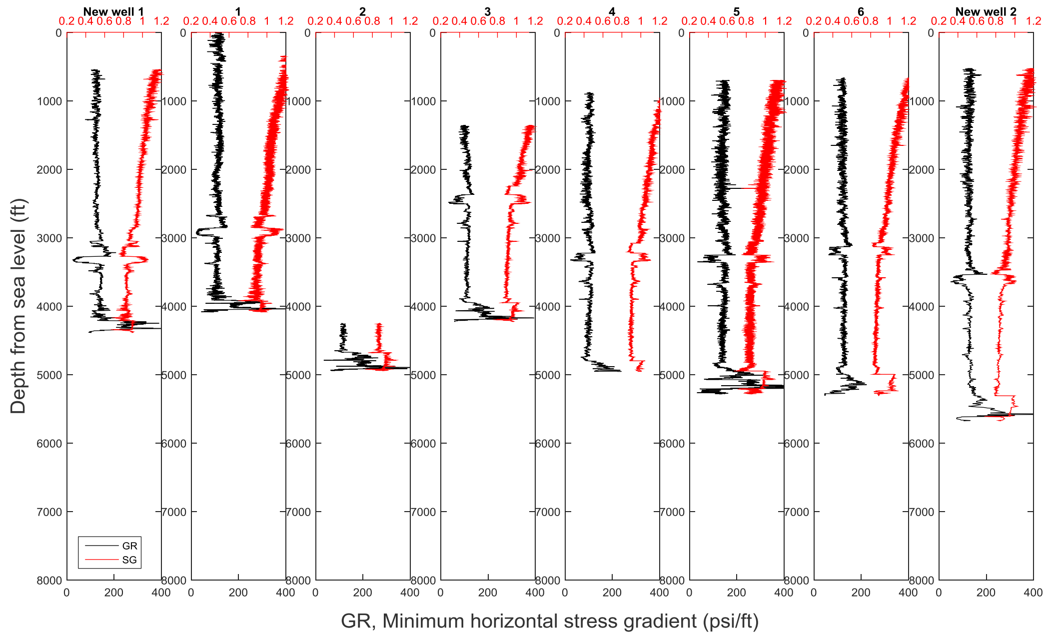

Figure 28: Superposition of gamma-ray and minimum horizontal stress gradient.

5 Conclusion

A basin-wide geomechanical model, the Appalachian Basin stress calculator (ABSC) app, is developed to predict the minimum horizontal stress in Appalachian Basin of Pennsylvania, Ohio and West Virginia. The app includes three main components, database, algorithm, and interface, and it is useful for the design of hydraulic fracture treatment before a well is drilled in the Appalachian Basin. The database integrates the gamma-ray and density logs of 476 wells, the well tops of seven mechanical units in the Devonian section, the basin-wide pore pressure distribution in Marcellus, and the tectonic strain in the Appalachian Basin. The algorithm adopts a poroelastic TIV model to predict the minimum horizontal stress, along with interpolation, extrapolation and correlation across the basin. The simple interface allows a user to input the location of a well, and output results including gamma-ray logs, density logs, mechanical properties, and minimum horizontal stress profile, for a new well and neighboring wells. Similar results along a cross section can also be output by inputting the locations of two wells.

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